



Early Journal Content on JSTOR, Free to Anyone in the World

This article is one of nearly 500,000 scholarly works digitized and made freely available to everyone in the world by JSTOR.

Known as the Early Journal Content, this set of works include research articles, news, letters, and other writings published in more than 200 of the oldest leading academic journals. The works date from the mid-seventeenth to the early twentieth centuries.

We encourage people to read and share the Early Journal Content openly and to tell others that this resource exists. People may post this content online or redistribute in any way for non-commercial purposes.

Read more about Early Journal Content at <http://about.jstor.org/participate-jstor/individuals/early-journal-content>.

JSTOR is a digital library of academic journals, books, and primary source objects. JSTOR helps people discover, use, and build upon a wide range of content through a powerful research and teaching platform, and preserves this content for future generations. JSTOR is part of ITHAKA, a not-for-profit organization that also includes Ithaka S+R and Portico. For more information about JSTOR, please contact support@jstor.org.

THE SCIENTIFIC MONTHLY

OCTOBER, 1915

THE EVOLUTION OF THE STARS AND THE FORMATION OF THE EARTH. II

BY DR. WILLIAM WALLACE CAMPBELL

DIRECTOR OF THE LICK OBSERVATORY, UNIVERSITY OF CALIFORNIA

THE PRINCIPLES OF SPECTROSCOPY

THUS far our description of the stellar universe has been confined to its geometrical properties. A serious study of the evolution of the stars must seek to determine, first of all, what the stars really are, what their chemical constitutions and physical conditions are; and how they are related to each other as to their physical properties. The application of the spectroscope has advanced our knowledge of the subject by leaps and bounds. This wonderful instrument, assisted by the photographic plate, enables every visible celestial body to write its own record of the conditions existing in itself, within limits set principally by the brightness of the body. Such records physicists have succeeded to some extent in duplicating in their laboratories; and the known conditions under which the laboratory experiments have been conducted are the Rosetta Stones which are enabling us to interpret, with more or less success, the records written by the stars.

It is well known that the ordinary image of a star, whether formed by the eye alone, or by the achromatic telescope and the eye combined, contains light of an infinite variety of colors corresponding, speaking according to the mechanical theory of light, to waves of energy of an infinite variety of lengths which have traveled to us from the star. In the point image of a star, these radiations fall in a confused heap, and the observer is unable to say that radiations corresponding to any given wave-lengths are present or absent. When the star's light has been passed through the prism, or diffracted from the grating of a spectroscope, these rays are separated one from another and arranged side by side in perfect order, ready for the observer to survey them and to determine which ones are present in superabundance and which other ones are lacking wholly or in part. The following comparison

is a fair one: the ordinary point image of a star is as if all the books in the university library were thrown together in a disorderly but compact pile in the center of the reading room: we could say little concerning the contents and characteristics of that library; whether it is strong in certain fields of human endeavor, or weak in other fields. The spectrum of a star is as the same library when the books are arranged on the shelves in complete perfection and simplicity, so that he who looks may appraise its contents at any or all points. Let us consider the fundamental principles of spectroscopy.

1. When a *solid body*, a *liquid*, or a *highly-condensed gas* is heated to incandescence, its light when passed through a spectroscope forms a *continuous spectrum*: that is, a band of light, red at one end and violet at the other, uninterrupted by either dark or bright lines.

2. The light from the *incandescent gas or vapor* of a chemical element, passed through a spectroscope, forms a *bright-line spectrum*; that is, one consisting entirely of isolated bright lines, distributed differently throughout the spectrum for the different elements, or of bright lines superimposed upon a relatively faint continuous spectrum.

3. If *radiations from a continuous-spectrum source* pass through *cooler gases or vapors* before entering the spectroscope, a *dark-line spectrum* results: that is, the positions which the bright lines in the spectra of the vapors and gases would have are occupied by dark or absorption lines. These are frequently spoken of as Fraunhofer lines.

To illustrate: the gases and vapors forming the outer strata of the Sun's atmosphere would in themselves produce bright-line spectra of the elements involved. If these gases and vapors could in effect be removed, *without changing underlying conditions*, the remaining condensed body of the Sun should have a continuous spectrum. The cooler overlying gases and vapors absorb those radiations from the deeper and hotter sources which the gases and vapors would themselves emit, and thus form the dark-line spectrum of the Sun. The stretches of spectrum between the dark lines are of course continuous-spectrum radiations.

These principles are illustrated in Fig. 12. The essential parts of a spectroscope are the slit—an opening perhaps $1/100$ th of an inch wide and $1/10$ th of an inch long—to admit the light properly; a lens to render the light rays parallel before they fall upon the prism or grating; a prism or grating; a lens to receive the rays after they have been dispersed by the prism or grating and to form an image of the spectrum a short distance in front of the eye, where the eye will see the spectrum or a sensitive dry-plate will photograph it. If we place an alcohol lamp immediately in front of the slit and sprinkle some common salt in the flame the two orange bright lines of sodium will be seen in the eyepiece, close together, as in the upper of the two spectra in the illustration. If we sprinkle thallium salt in the flame the green

line of that element will be visible in the spectrum. If we take the lamp away and place a lime light or a piece of white-hot iron in front of the slit we shall get a brilliant continuous spectrum not crossed by any

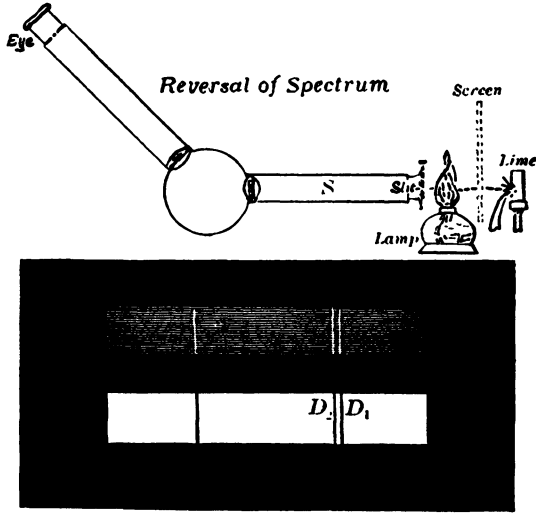


FIG. 12. THE SPECTROSCOPE.

lines, either bright or dark. Insert now the alcohol-sodium-thallium lamp between the lime light and the slit, and the observer will see the two sodium lines and one thallium line in the same places as before, but as dark lines on a background of bright continuous spectrum, as illustrated in the lower of the two spectra. Let us insert a screen between the lamp and the lime light so as to cut out the latter, and we shall see the bright lines of sodium and thallium reappear as in the upper of the two spectra. These simple facts illustrate Kirchhoff's immortal discovery of certain fundamental principles of spectroscopy, in 1859. The gases and vapors in the lamp flame are at a lower temperature than the lime source. The cooler vapors of sodium and thallium have the power of absorbing exactly those rays from the hotter lime or other similar source which the vapors by themselves would emit to form bright lines.

When we apply the spectroscope to celestial objects we find apparently an endless variety of spectra. We shall illustrate some of the leading characteristics of these spectra as in Figs. 13 to 18, inclusive, and Figs. 21, 22, 23 and 24. The spectra of some nebulae consist almost exclusively of isolated bright lines, indicating that these bodies consist of luminous gases, as Huggins determined in 1864; but a very faint continuous band of light frequently forms a background for the brilliant bright lines. Many of the nebular lines are due to hydrogen, others

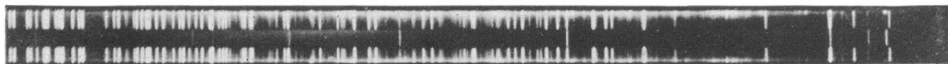
$H\delta$ $H\gamma$ $H\beta$ 

FIG. 13. SPECTRUM OF THE GREAT NEBULA IN ORION. Photographed at the Lick Observatory.

In Figs. 13, 14, 15, 16, 18, 21, 22 and 24, the series of bright lines along the upper edge and the lower edge of the illustrations are the reference spectrum of iron, obtained from the incandescent vapor of iron burned in the dome. The spectrum of the celestial object occupies the central strip (running right and left) in each illustration.

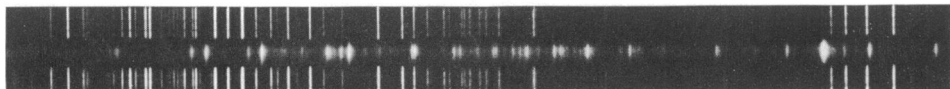
 $H\gamma$ $H\beta$ 

FIG. 14. SPECTRUM OF η CARINÆ. Photographed by the D. O. Mills Observatory.

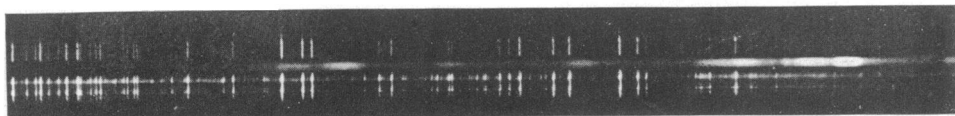
 $H\delta$ $H\gamma$ 

FIG. 15. SPECTRUM OF WOLF-RAYET STAR, B. D. +37.°3821. Photographed at the Lick Observatory.

4688

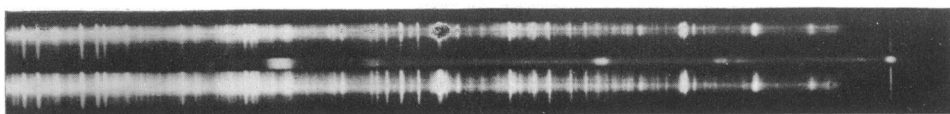
 $H\beta$ $H\alpha$ 

FIG. 16. SPECTRUM OF WOLF-RAYET STAR, A. G. C. 8,631. Photographed at the Lick Observatory.

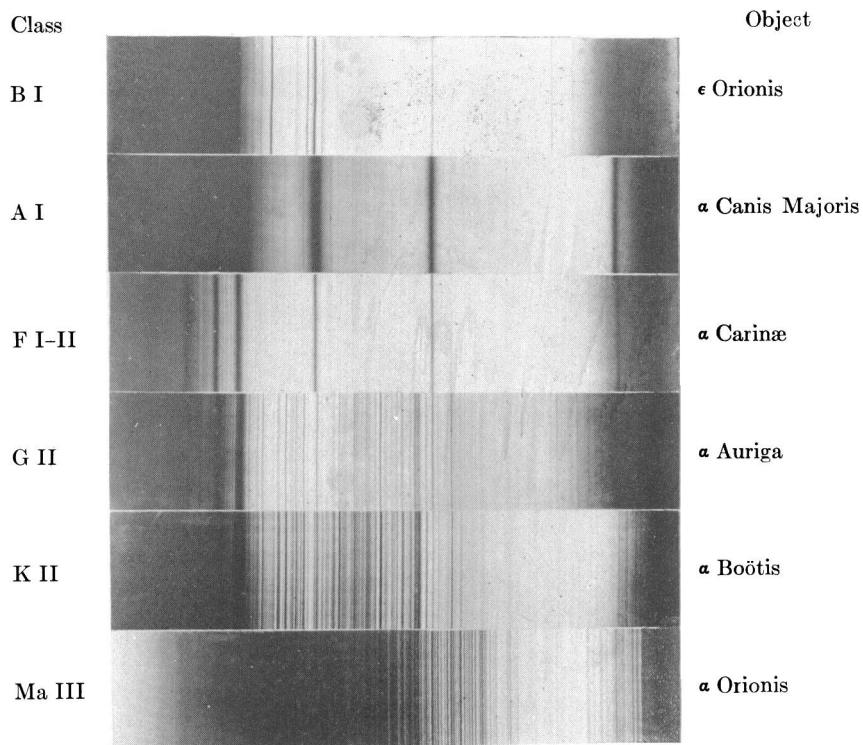


FIG. 17. TYPICAL SPECTRA. Photographed by the Harvard College Observatory Henry Draper Memorial.

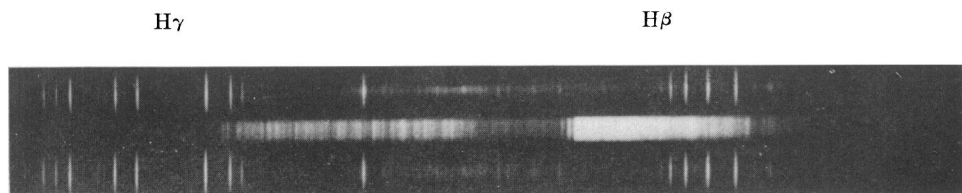


FIG. 18. CLASS N SPECTRUM, β CANUM VENATICORUM. Photographed at the Lick Observatory.



FIG. 19. THE "TRIFID" NEBULA, MESSIER 20, IN SAGITTARIUS. Photographed at the Lick Observatory.

are due to helium; but the majority, including the two on the extreme right in Fig. 13, which we attribute to the hypothetical element nebulium, and the close pair on the extreme left, have not been matched in our laboratories and, therefore, are of unknown origin. Most of the irregular nebulae whose spectra have been observed, the ring nebulae, the planetary and stellar nebulae, have very similar spectra, though with many differences in the details.⁶

The great spiral nebula in Andromeda has a continuous spectrum crossed by a multitude of absorption lines. The spectrum is a very close approach to the spectrum of our Sun. It is clear that this spiral nebula is widely different from the bright-line or gaseous nebulae in physical condition. The spiral may be a great cluster of stars which are approximate duplicates of our Sun, or there is a chance that it consists, as Slipher has suggested, of a great central sun, or group of suns, and of a multitude of small bodies or particles, such as meteoric matter, revolving around the nucleus; this finely divided matter being visible by reflected light which originates in the center of the system.

There is an occasional star, like η Carinae, whose spectrum consists almost wholly of bright lines, in general bearing no apparent relationship to the bright lines in the spectra of the gaseous nebulae except that the hydrogen lines are there, as they are almost everywhere. There is reason to believe that such a spectrum indicates the existence of a very extensive and very hot atmosphere surrounding the main body, or core, of the star in question. This particular star is remarkable in that it has undergone great changes in brilliancy and is located upon a background of nebulosity. The chances are strong that the star has rushed through the nebulosity with high rate of speed and that the resulting bombardment of the star has expanded and intensely heated its atmosphere.

There are the Wolf-Rayet stars, named from the French astronomers who discovered the first three of this class, whose spectra show a great variety of combinations of continuous spectrum and bright bands. We believe that the continuous spectrum in such a star comes from the more condensed central part, or core, and that the bright-line light proceeds from a hot atmosphere extending far out from the core.

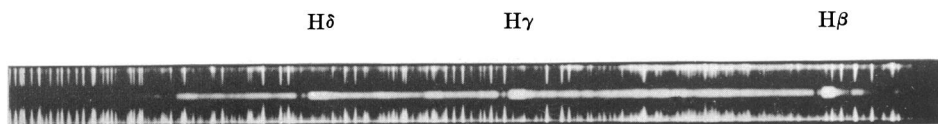
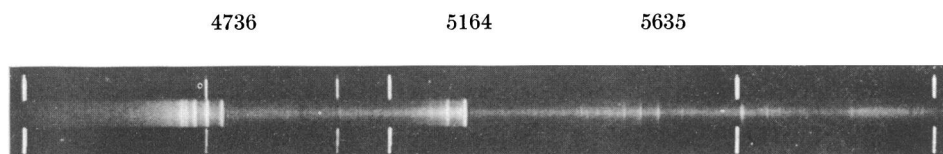
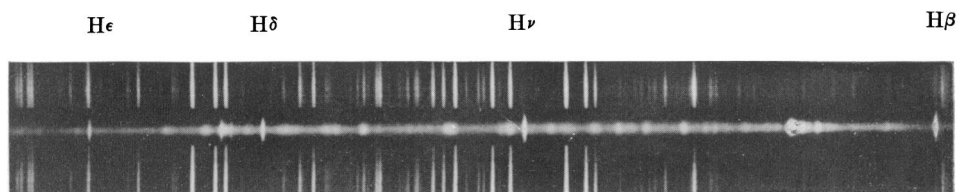
The great majority of the stars have spectra which are continuous, except for the presence of dark or absorption lines: a few lines in the very blue stars, and an increasing number of lines as we pass from the blue through the yellow and red stars to those which are extremely red.

Secchi in the late 60's classified the spectra of the brighter stars, according to the absorption lines in their spectra, into Types I, II, III and IV, which correspond: Type I, to the very blue stars, such as

⁶ My colleague, Wright, who has been making a study of the nebular spectra, has determined the accurate positions of about 67 bright nebular lines.



FIG. 20. THE PLEIADES NEBULA. Photographed at the Lick Observatory.
(By engraver's error, the plate is reversed in one direction.)



Spica and Sirius; Type II, to the yellow stars similar to our Sun; Type III, to the red stars such as Aldebaran; and Type IV, to the extremely red stars, of which the brightest representatives are near the limit of naked-eye vision. Secchi knew little or nothing concerning stars whose spectra contain bright lines, except as to the isolated bright-line spectra of a few nebulae, and as to the bright hydrogen lines in γ Cassiopeia, and his system did not include these.

One of the most comprehensive investigations ever undertaken by a single institution was that of classifying the stars as to their spectra, over the entire sky, substantially down to and including the stars of eighth magnitude, by the Harvard College Observatory, as a memorial to the lamented Henry Draper. Professor Pickering and his associates have formulated a classification system which is now in universal use. It starts with the bright-line nebulae, passes to the bright-line stars, and then to the stars in which the helium absorption lines are prominent. The latter are called the helium stars, or technically the Class B stars. The next main division includes the stars in which hydrogen absorption is prominent, called Class A. Classes B and A are blue stars. Then follows in succession Class F, composed of bluish-yellow stars, which is in a sense a transition class between the hydrogen stars and those resembling our Sun, the latter called Class G. The Class G stars are yellow. Class K stars are the yellowish-red; Class M, the red; and Class N, the extremely red. Each of these classes has several subdivisions which make the transition from one main class to the next main class fairly gradual, and not per saltum; though it should be said that the relationship of Class N to Class M spectra is not clear. The illustration, Fig. 17, brings out the principal features of the spectra of Classes B to M. The spectrum becomes more complicated as we pass from Class B to the Class M, and the color changes from blue to extreme red, because the violet and blue radiations become rapidly weaker as we pass through the various classes.

GENERAL COURSE OF EVOLUTIONARY PROCESS

The general course of the evolutionary processes as applied to the principal classes of celestial bodies is thought to be fairly well known. With very few exceptions astronomers are agreed as to the main trend of this order, but this must not be interpreted to mean that there are no outstanding differences of opinion. There are, in fact, some items of knowledge which seem to run counter to every order of evolution that has been proposed.

The large irregular nebulae, such as the great nebula in Orion, the Trifid nebula, and the background of nebulosity which embraces a large part of the constellation of Orion, are thought to represent the earliest form of inorganic life known to us. The material appears to

be in a chaotic state. There is no suggestion of order or system. The spectroscope shows that in many cases the substance consists of glowing gases or vapors; but whether they are glowing from the incandescence resulting from high temperature, or electrical condition, or otherwise, is unknown, though heat origin of their light is the simplest hypothesis now available. Whether such nebulae are originally hot or cold, we must believe that they are endowed with gravitational power, and that their molecules or particles are, or will ultimately be, in motion. It will happen that there are regions of greater density, or nuclei, here and there throughout the structure which will act as centers of condensation, drawing surrounding materials into combination with them. The processes of growth from nuclei originally small to volumes and masses ultimately stupendous must be slow at first, relatively more rapid after the masses have grown to moderate dimensions and the supplies of outlying materials are still plentiful, and again slow after the supplies shall have been largely exhausted. By virtue of motions prevailing within the original nebular structure, or because of inrushing materials which strike the central masses, not centrally but obliquely, low rotations of the condensed nebulous masses will occur. Stupendous quantities of heat will be generated in the building-up process. This heat will radiate rapidly into space because the gaseous masses are highly rarefied and their radiating surfaces are large in proportion to the masses. With loss of heat the nebulous masses will contract in volume and gradually assume forms more and more spherical. When the forms become approximately spherical, the first stage of stellar life may be said to have been reached.

It was Herschel's belief that by processes of condensation, following the loss of heat by radiation into surrounding space, formless nebulae gravitated into nebulae of smaller and smaller volumes until finally the planetary form was reached, and that planetaries were the ancestors of stars in general. That the planetaries do develop into stars, we have every reason to believe; but that all nebulae, or relatively many nebulae, pass through the planetary stage, or that many of our stars have developed from planetaries, we shall later find good reason for doubting. The probabilities are immensely stronger that the stars in general have been formed directly from the irregular nebulae, without the intervention of the planetaries. The planetary nebulae seem to be exceptional cases, but to this point we shall return later.

It is quite possible, and even probable, that gaseous masses have not in all cases passed directly to the stellar state. The materials in a gaseous nebula may be so highly attenuated, or be distributed so irregularly throughout a vast volume of space, that they will condense into solids, small meteoric particles for example, before they combine to form stars. Such masses or clouds of non-shining or invisible matter

are thought to exist in considerable profusion within the stellar system. The nebulosity connected more or less closely with the brighter Pleiades stars may be a case in illustration. Slipher has recently found that the spectra of two small regions observed in this nebula are continuous, with absorption lines of hydrogen and helium. This spectrum is apparently the same as that of the bright Pleiades stars. Slipher's interpretation is that the nebula is not shining by its own light, but is reflecting to us the light of the Pleiades stars. That this material will eventually be drawn into the stars already existing in the neighborhood, or be condensed into new centers and form other stars, we can scarcely doubt. The condensation of such materials to form stars large enough to be seen from the great distance of the Pleiades cluster must generate heat in the process, and cause these stars in their earliest youth to be substantially as hot as other stars formed directly from gaseous materials. It is possible, also, that the spiral nebulae will develop into stars, perhaps each such object into many, or some of the larger ones into multitudes, of stars.

Let us attempt to visualize the conditions which we think exist in a newly-formed star of average mass. It should be essentially spherical, with surface fairly sharply defined. Our Sun has average specific gravity of 1.4, as compared with that of water. The average density of the very young star must certainly be vastly lower; perhaps no greater than the density of our atmosphere at the Earth's surface; it may even be considerably lower than this estimate. The diameter of our Sun is 1,400,000 kilometers. The diameter of the average young star may be ten or twenty or forty times as great. The central volume or core of the star is undoubtedly a great deal denser than the surface strata, on account of pressure due to the star's own gravitational forces. The conditions in the outer strata should bear some resemblance to those existing in the gaseous nebula. The star may or may not have a corona closely or remotely similar to our Sun's corona. The deep interior of the star must be very hot, though not nearly so hot as the interiors of older stars; but the surface strata of the young star should be remarkably hot; for, being composed of highly attenuated gases, any lowering of the temperature by radiation into surrounding space will be compensated promptly through the medium of highly-heated convection currents which can travel more rapidly from the interior to the surface than in the case of stars in middle or old age. Even though the star, as observed in our most powerful telescopes, is a point of light, without apparent diameter, its outer strata should supply some bright lines in the spectrum, because these strata project out beyond what we may call the core of the star and themselves act as sources of light. The spectrum should, therefore, consist of some of the bright lines which were observed in the nebular spectrum, these proceeding from the

outer strata of the star; and of a continuous spectrum made up of radiations proceeding from the deeper strata or core of the star, in which a few dark lines may be introduced by the absorption from those parts of the outer gaseous strata which lie between us and the core.

A few hundred stellar spectra resembling this description are well known, discovered mostly at the Harvard Observatory. Their details differ greatly, but they have certain features in common. The bright lines of helium are extremely rare in stars, but they have been observed in a few stellar spectra. The bright lines of nebulium have never been observed in a true star: they and the radiations in the ultra-violet known as at 3726A, seem to be confined to the nebular state; and the absorption lines of nebulium have never been observed in any spectrum. As soon as the stellar state is reached nebulium is no longer in evidence. Stellar spectra containing bright lines seem always to include hydrogen bright lines. This is as we should expect; hydrogen is the lightest known gas, and it is probably the substance which can best exist in the outer strata of stars in general. The extensive outer strata of very young stars seem to be composed largely of hydrogen, though other elements are in some cases present, as indicated by the weaker bright lines in a few cases. This preference of hydrogen for the outermost strata is illustrated by several very interesting observations of the nebulae. The nebulium lines are relatively strong in the central denser parts of the Orion and Trifid nebulae, but the hydrogen bright-lines are relatively very strong in the faint outlying parts of these nebulae. The planetary nebula B.D. — 12°.1172 is seen in the ordinary telescope to consist of a circular disc (probably a sphere or spheroid) of light and a faint star in its center. When this nebula is observed with a slitless spectrograph the hydrogen and nebulium components are seen as circular discs, but the hydrogen discs are larger than the nebulium discs. In other words, the hydrogen forms an atmosphere about the central star which extends out into space in all directions a great deal farther than the nebulium discs extend. The Wolf-Rayet star-planetary nebula D. M. + 30°.3639 looks hazy in a powerful telescope, and when examined in a spectroscope the haziness is seen to be due to a sharply defined globe of hydrogen 5 seconds of arc in diameter surrounding the star in its center. Wolf and Burns have shown that in the Ring Nebula in Lyra the 3726A and the hydrogen images are larger as to outer diameter than the nebulium images, but that the latter are the more condensed on the inner edge of the ring. Wright has in the present year examined these and other nebulae with special reference to the distribution of the principal ingredients. He finds in general that the radiations at 4363A and 4686A, of unknown or possibly helium origin, are most closely compressed around the central nuclei of nebulae; that the matter definitely known to be helium is more extended in size;

that the nebulium structure is still larger; and that the hydrogen uniformly extends out farther than the nebulium; and that the ultra violet radiation at 3726A seems to proceed from the largest volume of all. The 3726A line, like the nebulium line, is unknown in stellar spectra; it seems also to be confined to true nebulosity. Neglecting the elements which have never been observed in true stars, we may say that all these observations are in harmony with the view that hydrogen should be and is the principal element in the outer stratum of the very young star. A few of the stars whose spectra contain bright hydrogen lines have also a number of bright lines whose chemical origin is not known. They appear to exist exactly at this state of stellar life: several of them have not been found in the spectra of the gaseous nebulæ, and they are not represented in the later types of stellar spectra. The strata which produce these bright lines are thought to be a little deeper in the stars than the outer hydrogen stratum.

A slightly older stage of stellar existence is indicated by the type of spectrum in which some of the lines of hydrogen, always those at the violet end, are dark, and the remaining hydrogen lines, always those toward the red end, are bright. The brightest star in the Pleiades group, Alcyone, presents apparently the last of this series, for all of the hydrogen lines are dark except $H\alpha$, in the red. In some of the bright-line stars which we have described, technically known as Oe5, Harvard College Observatory found that the dark helium and hydrogen lines exist, and apparently increase in intensity, on the average, as the bright lines become fainter. Wright has observed the absorption lines of helium and hydrogen in the spectra of the nuclei of some planetary nebulæ, although the helium and hydrogen lines are bright in the nebulosity surrounding the nuclei. We may say that when all of the bright lines have disappeared from the spectra of stars, the helium lines, and likewise the hydrogen lines, have in general become fairly conspicuous. These stars are known as the helium stars, or stars of Class B. Proceeding through the subdivisions of Class B, the helium lines increase to a maximum of intensity and then decrease. The dark hydrogen lines are more and more in evidence, with intensities increasing slowly. In the middle and later subdivisions of the helium stars silicon, oxygen and nitrogen are usually represented by a few absorption lines.

Just as the gaseous nebulæ radiate heat into space and condense, so must the stars, with this difference: the nebulæ are highly rarified bodies, with surfaces enormously large in proportion to the heat contents; and the radiation from them must be relatively rapid. In fact, some of the nebulæ seem to be so highly rarified that radiation may take place from their interiors almost as well as from their surfaces. The radiation from a star just formed must occur at a much slower

rate. The continued condensation of the star, following the loss of heat, must lead to a change of physical condition, which will be apparent in the spectrum. It should pass from the so-called helium group, to the hydrogen, or Class A group, not suddenly but by insensible gradations of spectrum. In the Class A stars the hydrogen lines are the most prominent features. The helium lines have disappeared, except in a few stars where faint helium remnants are in evidence. The magnesium lines have become prominent and the calcium lines are growing rapidly in strength. The so-called metallic lines, usually beginning with iron and titanium lines, which have a few extremely faint representatives in the last of the helium stars, become visible here and there in the Class A spectra, but they are not conspicuous.

In the next main division, the Class F spectra, the metallic lines increase rapidly in prominence, and the hydrogen lines decrease slightly in strength. These stars are not so blue as the helium and hydrogen stars. They are intermediate between the blue stars and the yellow stars, which begin with the next class, G, of which our Sun is a representative.

The metallic lines are in Class G spectra in great number and intensity, and the hydrogen lines are greatly reduced in prominence. The calcium bands are very wide and intense.

Another step brings us to the very yellow and the slightly-reddish stars, known as Class K. These stars are weak in violet light, the hydrogen lines are substantially of the same intensity as the most prominent metallic lines, and the metallic lines are more and more in evidence.

Stars in the last subdivisions of the Class K and all of the Class M stars are decidedly red. In these the hydrogen lines are still further weakened and the metallic lines are even more prominent. Their spectra are further marked by absorption bands of titanium oxide, which reach their maximum strength in the later subdivisions of Class M.

The extremely red stars compose Class N on the Harvard scale. Their spectra are almost totally lacking in violet light, the metallic absorption is very strong, and there are conspicuous absorption bands of carbon.

Deep absorbing strata of titanium and carbon oxides seem to exist in the atmospheres of the Class M and N stars, respectively. The presence of these oxides indicates a relatively low temperature, and this is what we should expect from stars so far advanced in life.

The period of existence succeeding the very red stars has illustrations near at hand, we think, in Jupiter, Saturn, Uranus and Neptune, and in the Earth and the other small planets and the Moon: bodies which still contain much heat, but which are invisible save by means of reflected light.

The progression of stellar development, which we have described, has been based upon the radiation of heat. This is necessarily gradual, and the corresponding changes of spectrum should likewise be gradual and continuous. It is not intended to give the impression that only a few types of spectra are in evidence: the variety is very great. The labels, Class B, Class A, and so on to Class N, are intended to mark the miles in the evolutionary journey. The Harvard experts have put up other labels to mark the tenths of miles, so to speak, and some day we shall expect to see the hundredths labeled. Further, it is not here proposed that heat radiation is the only vital factor in the processes of evolution. The mass of a star may be an important item, and the electrical conditions may be concerned. A very small star and a very massive star may develop differently, and it is conceivable that there may be actual differences of composition. But heat-radiation is doubtless the most important factor.

The evolutionary processes must proceed with extreme deliberation. The radiation of the heat actually present at any moment in a large helium star would probably not require many tens of thousands of years, but this quantity of heat is negligible in comparison with the quantity generated within the star during and by the processes of condensation from the helium age down to the Class M state. We know that the compression of any body against resistance generates or releases heat. Now a gaseous star at any instant is in a state of equilibrium. Its internal heat and the centrifugal force due to its rotation about an axis are trying to expand it. Its own gravitational power is trying to draw all of its materials to the center. Until there is a loss of heat no contraction can occur; but just as soon as there is such a loss gravity proceeds to diminish the stellar volume. Contraction will proceed more slowly than we should at first thought expect, because in the process of contraction additional heat is generated and this becomes a factor in resisting further compression. Contraction is resisted vastly more by the heat generated in the process of contraction than it is by the store of heat already in evidence. The quantity of heat in our Sun, now existing as heat, would suffice to maintain its present rate of outflow only a few thousands of years. The heat generated in the process of the Sun's shrinkage under gravity, however, is so extensive as to maintain the supply during millions of years to come. Helmholtz has shown that the reduction of the Sun's radius at the rate of 45 meters per year would generate as much heat within the Sun as is now radiated. This rate of shrinkage is so slow that our most refined instruments could not detect a change in the solar diameter until after the lapse of 4,000 or 5,000 years. Again, there are reasons for suspecting that the processes of evolution in our Sun, and in other stars as well, may be enormously prolonged through the influence of energy within the atoms or

molecules of matter composing them. The subatomic forces residing in the radioactive elements represent the most condensed form of energy of which we have any conception. It is believed that the subatomic energy in a mass of radium is at least a million-fold greater than the energy represented in the combustion or other chemical transformation of any ordinary substance having the same mass. These radioactive forces are released with extreme slowness, in the form of heat or the equivalent; and if these substances exist moderately in the Sun and stars, as they do in the Earth, they may well be important factors in prolonging the lives of these bodies.

Speaking somewhat loosely, I think we may say that the processes of evolution from an extended nebula to a condensed nebula and from the latter to a spherical star, are comparatively rapid, perhaps normally confined to a few tens of millions of years; but that the further we proceed in the development process, from the blue star to the yellow, and possibly but not certainly on to the red star, the slower is the progress made, for the radiating surface through which all the energy from the interior must pass becomes smaller and smaller in proportion to the mass, and the convection currents which carry heat from the interior to the surface must slow down in speed.